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Ocean XR: A Deep Dive Into Extended Reality for Marine Education and Ocean Literacy

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Abstract

Contact with the ocean is key to improving ocean literacy (OL)—the understanding of our influence on the ocean and the ocean's influence on us. Ocean extended reality (ocean XR) can contribute to marine education and OL by simulating marine environments using augmented, mixed, and virtual reality technologies. To better understand this emerging field, we analyzed 94 experiences revealing insight into the usage and effects of key extended reality features: presence, interactivity, and embodiment. Virtual wildlife was present in over 75% of content, though wildlife interactions were less common (42%) than interactions with the environment (72%). Embodiment was featured in 49% of experiences, and 30% placed users in a scientific role. Most simulations (88%) featured at least one OL principle, with correlations suggesting positive relationships between OL principles and key features. This work represents a first step in understanding how ocean extended reality can benefit marine education and OL and offers suggestions for creating more impactful virtual ocean experiences.

Keywords

augmented reality; extended reality; immersive technologies; marine environmental education; mixed reality; ocean literacy; virtual reality

1. Introduction

Human communities benefit from the ocean, which harbors marine biodiversity that supports fishing, tourism, and pharmaceuticals (Malve, 2016). The ocean also buffers the global climate and provides extensive economic resources through shipping, aquaculture, minerals, and energy creation (OECD, 2016). Beyond this service-based approach, it is our duty to care for marine ecosystems as part of the legacy we borrow from our children (Na'puti, 2023). However, ocean resources are degrading from human activities through habitat destruction, overfishing, pollution, and the effects of climate change (Heinze et al., 2021). The UN Decade of Ocean Science for Sustainable Development (2021–2030) calls for "an inspiring and engaging ocean where society understands and values the ocean in relation to human well-being and sustainable development," an outcome that "can be achieved through ocean literacy approaches" (UNESCO-IOC, 2021, p. 19) The concept of ocean literacy (OL) relates to one's ability to understand their influence on the ocean and the ocean's influence on them (Cava et al., 2005). While OL was defined 20 years ago to address the lack of ocean-related content in US schools, it has since become a global movement to improve our relationship with the ocean.

The nature of the ocean makes it difficult to experience or understand, as only people living near coastlines see the ocean on a regular basis (Fauville, McHugh, et al., 2018). Even for these people, most of the ocean is still inaccessible below the surface and beyond the coast. Digital technologies can be valuable when interaction with the natural world is impossible or when an invisible phenomenon needs to be made more tangible. While the remote nature of the physical ocean cannot be changed, immersion in and experience with the ocean can be mimicked with immersive media. Extended reality (XR) modalities like augmented, mixed, and virtual realities have unique affordances that simulate experiences more effectively than videos on screens (Bailenson, 2018). This capability is determined in part by the specific XR modality's placement along the spectrum of virtuality, a continuum articulating the extent to which digital content coexists and/or replaces the physical world (Figure 1):

- Augmented reality (AR) enriches the physical space observed through the camera of mobile devices by superimposing digital content such as 3D objects, text, and sound.
- Mixed reality (MR) uses see-through head-mounted displays (HMDs) to integrate digital content naturally into the physical world.
- Virtual reality (VR) requires an HMD that visually isolates the user from the physical world and immerses them completely in a virtual environment.

In XR, users can interact with the content and visualize invisible concepts (e.g., molecules). VR has shown potential to promote pro-environmental behavior (Plechatá et al., 2022; Stenberdt & Makransky, 2023), nature connectedness (Breves & Heber, 2020), and knowledge gain (Markowitz et al., 2018). However, more research is needed to understand how XR can improve marine environmental education and promote OL. This study contributes to those goals in two ways. First, we identified the existing XR content related to the ocean (called ocean XR experiences or ocean XR content hereafter). Second, we conducted a content analysis of these ocean XR experiences to form an initial understanding of their (a) product information, (b) unique design features, and (c) contributions to OL. This analysis is crucial to identify key features and challenges to drive future research and best practices (Stephens et al., 2017).

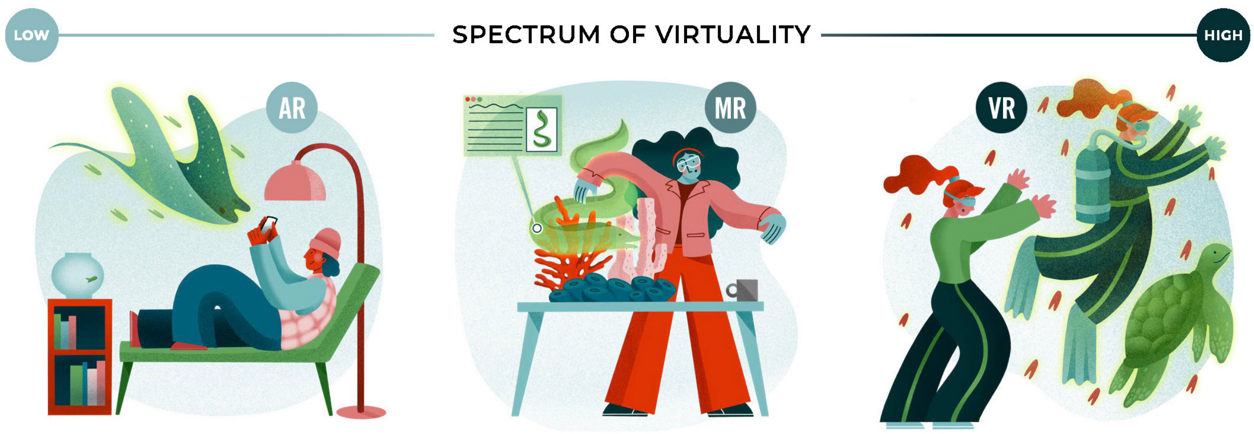

Figure 1. Spectrum of virtuality: demonstrating AR, MR, and VR. Note: Illustration by Halsey Berryman. Source: Pimentel et al. (2022).

2. Theoretical Background

2.1. The Landscape of Ocean XR Content

Ocean XR experiences exist in the wider context of the XR landscape, influenced by creator and user communities as well as economic forces, international participation, and technological advancements. The current study therefore seeks to understand ocean XR's place within XR content through variables including release year, XR modality, price, presence or absence of in-app purchase, entity responsible for the content, name of the developer, countries involved in the creation of the content, languages in which the content of the XR experience is available, and hardware on which the content is available.

2.2. Ocean XR Affordances

In XR technologies, the coexistence—or replacement—of the real world with digital content results in experiences that are immersive and feel realistic (Cummings & Bailenson, 2016). This perceptual similarity between XR-based and real-world experiences is driven by four key affordances that guided the choice of variables we coded each ocean XR experience for: interactivity, spatial presence, social presence, and body transfer.

Interactivity is defined as a system's capacity to enable users to modify aspects of a simulated experience and is known to mediate human responses to content in various contexts (Kalyanaraman & Wojdynski, 2015). XR facilitates experiences that enable rich information exchanges in part due to its capacity for natural interactivity (Lege, 2024). It is integral to understand interactive features across XR content given their capacity for shaping cognitive and affective responses. For example, one unique interactive property in XR is its degrees of freedom (DoF), which determines a user's interaction levels: 6 DoF allows full spatial exploration, while 3 DoF restricts to pitch, yaw, and roll. Interaction with the natural environment, or with environmental issues, is key for environmental education as it promotes pro-environmental concerns (Hinds & Sparks, 2008), attitudes and behavior (Bergquist et al., 2019), along with environmental risk perception (van der Linden, 2015). To investigate the role of interactivity in ocean XR content, we coded the DoF of XR content, the interaction with wildlife, and environmental interaction.

Spatial presence is a feeling of being physically located in the virtual environment. The perceptual similarity between XR-based and real-world experiences is rooted in the XR's ability to elicit a genuine sense of spatial presence (Steuer, 1992). Physical distance can be a barrier to experiencing and understanding natural environments. XR tools can create digital experiences that feel realistic, where one experiences spatial presence. To investigate aspects of spatial presence in ocean XR content, we coded for the presence of wildlife and depiction of environmental issues.

Social presence is defined as the subjective sense of being with other characters (human- or computer-controlled) in a mediated environment (Oh et al., 2018). XR can create a sense of proximity to mediated others, reducing psychological distance and increasing identification with them (Pimentel & Kalyanaraman, 2022). Identification refers to the extent to which a user perceives a social referent as self-similar, a factor shown to increase learning outcomes such as self-efficacy (Peng, 2008) and motivation (Birk et al., 2016). To investigate social presence among ocean XR content, we investigated multiplayer functionality, meaning the option to interact with other users in the experience.

Body transfer is the illusory sense of ownership over one's virtual body achieved via correspondence between the user's physical and virtual body movements (Botvinick & Cohen, 1998; Slater et al., 2010). Embodied cognition theory argues that cognition is a product of an individual's (virtual) body and its relationship to the (virtual) world (Shapiro & Stolz, 2019). XR's capacity for embodiment of virtual characters (avatars), therefore, can enhance user learning and engagement (Scavarelli et al., 2021) through various means, including simulated (direct) interactions with subject matter that constitutes experiential learning and encourages heightened attention on learning. For example, users' physical movements can promote understanding of abstract concepts in science, technology, engineering, and math (STEM) education (Kang et al., 2021). The role of XR for STEM education through embodiment has therefore been of significant interest to educators and researchers. Pimentel and Kalyanaraman (2022) invited students to become paleoclimatologists in VR and observed increases in positive views of science—and of becoming a scientist—across gender and race, with the most prominent increases in female and African American students. In another study, the user takes on the role of a professional rehabilitating oil-covered penguins in AR, leading to increased connectedness with the animals (Pimentel, 2022). Further studies have investigated how stepping into the shoes of a marine scientist, interacting with CO_2 molecules, and performing a species count in an acidified ocean environment can contribute to learners' self-efficacy (Queiroz et al., 2023) and knowledge gain (Markowitz et al., 2018). To address body transfer in the ocean XR content, we coded for embodiment and taking on a STEM or expert role.

2.3. OL Principles Addressed in Ocean XR Experiences

The OL movement, composed of policymakers, scientists, educators, and education researchers, started in the early 2000s to address the lack of marine-related content in formal US science education. They sought consensus about what people graduating from high school should understand to be considered ocean literate. This resulted in 7 overarching ideas, called the essential ocean literacy principles (OLPs; Figure 2) and 45 fundamental concepts that support and add details to the OLPs (National Oceanic and Atmospheric Administration, 2024). To investigate how ocean XR content contributes to OL, we identified which OLPs were addressed in each ocean XR experience.

1. Earth has one big ocean with many features
2. The ocean and life in the ocean shape the features of Earth
3. The ocean is a major influence on weather and climate
4. The ocean makes Earth habitable
5. The ocean supports a great diversity of life and ecosystems
6. The ocean and humans are inextricably interconnected
7. The ocean is largely unexplored

Figure 2. The seven OLPs. Note: See National Oceanic and Atmospheric Administration (2024), for a list of the seven OLPs and their 45 fundamental concepts.

2.4. Relationship Between OLPs and Ocean XR Features

The interplay between technological features and educational content is important to understand learning outcomes in any mediated form of communication (Choi & Baek, 2011). Since each OLP addresses a distinct topic related to the ocean, some XR features—like interactivity, social presence, and body transfer—might be more suitable for certain principles than others. XR researchers have begun exploring the features of these tools for learning (Pimentel & Kalyanaraman, 2022; Scavarelli et al., 2021), and marine education researchers have investigated methods for teaching OLPs (e.g., Boaventura et al., 2021) and measuring OL among learners worldwide (Fauville, Strang, et al., 2018). To our knowledge, no work has been done to assess how XR and OL relate to each other. We therefore sought to explore the alignment of these key XR features with the OLPs, namely, whether there were associations between design features of immersive media and particular OLPs.

3. Materials and Methods

To better understand the ocean XR landscape and its capacity to advance OL, we conducted a content analysis, defined as a “systematic and objective quantitative analysis” (Neuendorf, 2017, p. 1), of available ocean XR experiences. This type of analysis is typically used to examine messaging in text, drawings, video, or games (Stemler, 2000). In this study, we extend this methodology to include publicly available AR, MR, and VR experiences.

3.1. Search for Ocean XR Content

Queries were prompted between January and February 2023 across commercially available online marketplaces (see Supplementary File, Table A) to compile a list of AR, MR, and VR experiences related to the ocean. The search criteria consisted of any combination of the following terms: “ocean,” “marine,” “sea,” “water,” and “reef.” The researchers relied on industry and academic networks to retrieve ocean XR experiences that were not listed on the public marketplaces but were publicly available through various channels (e.g., museum exhibits).

A total of 109 ocean XR experiences were identified, and 94 were included in our analysis (Figure 3). One duplicate was removed, and 14 others were removed for any one of three reasons: (1) they were standalone 360-degree videos (3 DoF), and therefore outside the scope of this work because they do not feature on the XR spectrum of virtuality, thus meriting their own investigations; (2) they did not integrate the ocean into aspects of the gameplay and/or narrative, for example, XR experiences that only featured the ocean as scenery and 3D asset viewers with AR capabilities were removed; and (3) they were not downloadable or functional.

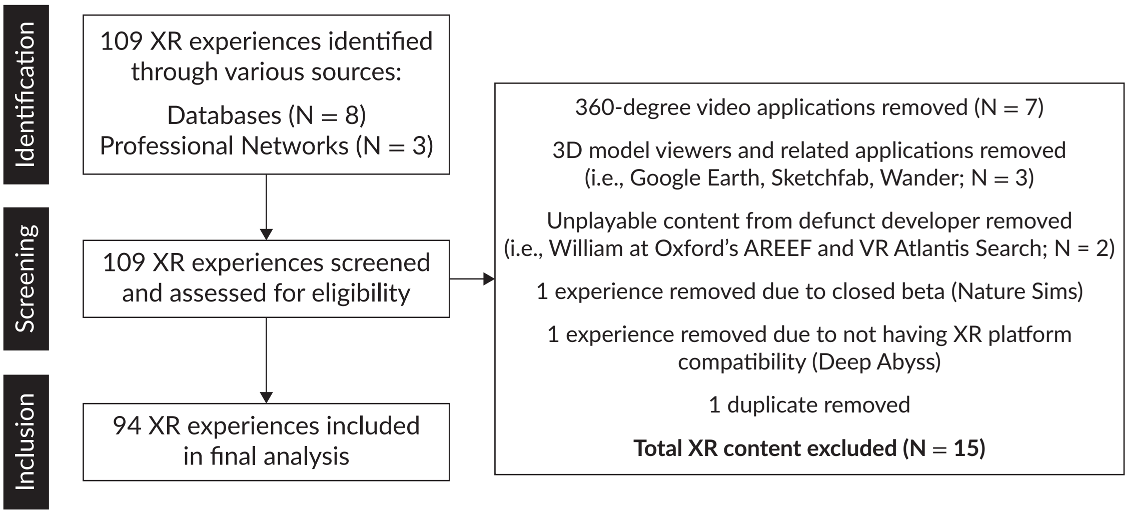

Figure 3. Preferred reporting items for systematic reviews and meta-analyses (PRISMA) flowchart.

3.2. Codebook

A codebook gathering the variables and their respective codes was developed based on existing theories and concepts relevant to the fields of XR and OL. Six coders iteratively designed the codebook (Bernard & Ryan, 2010). The final codebook included 23 variables divided into three sub-categories: product information, design features, and OL alignment.

3.2.1. Product Information

To understand the ocean XR landscape, eight variables were identified to describe the structural and logistical characteristics of ocean XR content:

1. Release year: The year the XR experience was released. If the same experience was launched multiple times on different platforms or for different hardware, the earliest year was used.

2. XR modality: The XR modality used to access the content, i.e., AR, MR, or VR (Figure 4).

3. Price: The price (in USD) of the XR experience, as listed during data collection.

4. In-app purchases: Whether the experience allows users to spend money for in-game content.

5. Responsible entity: The entity responsible for the development and/or distribution of the ocean XR experience based on the available public-facing information (e.g., marketplaces, product website, etc.). The options were "NGO," "government agency," "company," "individual creator," and "multiple partners" when more than one of the previous options applied. Along with coding for the kind of entity listed, we listed the name of the developer.

6. Countries: The number of countries (and their names) involved in the creation of the XR experience.

7. Languages: The number and names of languages supported by the XR experience; language support could range from captions to narration.

8. Hardware: All hardware compatible with the XR experience.

Figure 4. Examples of ocean XR content included in the analyses: (a) AR Reef (AR), (b) Undersea (MR), and (c) The Blu (VR).

3.2.2. Ocean XR Features

To uncover how XR features contribute to ocean XR content, we coded for the absence (a) or presence (b) of the following variables:

- Multiplayer functionality: allows cooperative play.
- Six DoF: enables user movements across all 6 spatial axes (roll, pitch, yaw, surge, sway, and heave).
- Wildlife presence: contains visual representations of living organisms. We also listed which organisms appeared.
- Wildlife interactions: user actions (e.g., button presses) elicit responses from depicted wildlife. A third code, "N/A," was used when the ocean XR content did not depict any wildlife.
- Environmental interactions: allows users to control or manipulate digital objects.
- Embodiment: allows the user to embody, or be visually represented by, an avatar by featuring part of the user's body in real-time.
- STEM role: allows users to assume the role, either via narrative and/or gameplay, of a STEM professional or technical expert.
- Environmental threat depiction: features any human-caused environmental threat.

3.2.3. OLPs in Ocean XR Experiences

We also coded for the absence (a) or presence (b) of alignment between each ocean XR experience and each of the OLPs (Figure 1). Figure 5 illustrates how two ocean XR experiences align with OLPs. The Ocean Week Canada AR experience features OLP5 ("the ocean supports a great diversity of life and ecosystems") by showcasing animated digital models of various species of whales and dolphins. The Stanford Ocean Acidification Experience in VR addresses OLP3 ("the ocean is a major influence on weather and climate") by describing how the ocean absorbs a significant portion of the carbon dioxide added to the atmosphere, and OLP6 ("the ocean and humans are inextricably connected") by explaining how human activities are responsible for changing the pH of the ocean.

Figure 5. Examples of the alignment of XR experiences and OLPs. Note: Specific OLPs are overlaid on a screengrab of each experience.

3.3. Coding Ocean XR Experiences

Six coders conducted the content analysis. For each XR experience, guided by the 23 variables of the codebook, they (a) found product information, (b) examined the experiences' content, and (c) assessed alignment with OLPs. Coders played each assigned XR simulation, either in its entirety or for 30 minutes, which represents an average session time for VR (Steam, 2021) and the battery life for commercially available AR headsets (BBC News, 2021), whichever criterion was met first. To assess inter-rater reliability, coders reviewed, discussed, and clarified the codebook before independently coding 10 XR experiences. We used Gwet's AC1 statistic for its suitability with binary coding schemes and uneven distribution responses (Ohyama, 2021), as most XR experiences were coded as not having OLPs meaningfully integrated. Gwet's AC1 is also a strong alternative to other reliability measures (e.g., Kappa; Jimenez & Zepeda, 2020). When reliability was below a moderate level, researchers discussed the codes again, clarified the interpretation of the variables, modified them, and independently re-analyzed a new set of 10 experiences. Three iterations were needed. All AC1 values achieved a fair (> 0.21), moderate (> 0.41), or high agreement (> 0.61), ranging from 0.31 to 0.97 (see Walsh et al., 2022). The p-values for each code were significant (all p's < 0.001).

4. Results

4.1. The Landscape of Ocean XR Content

The publication dates of the 94 XR experiences analyzed ranged from 2014 to April 2023, when data collection stopped (Figure 6). The dataset consisted of 26 experiences in AR, 5 in MR, and 63 in VR.

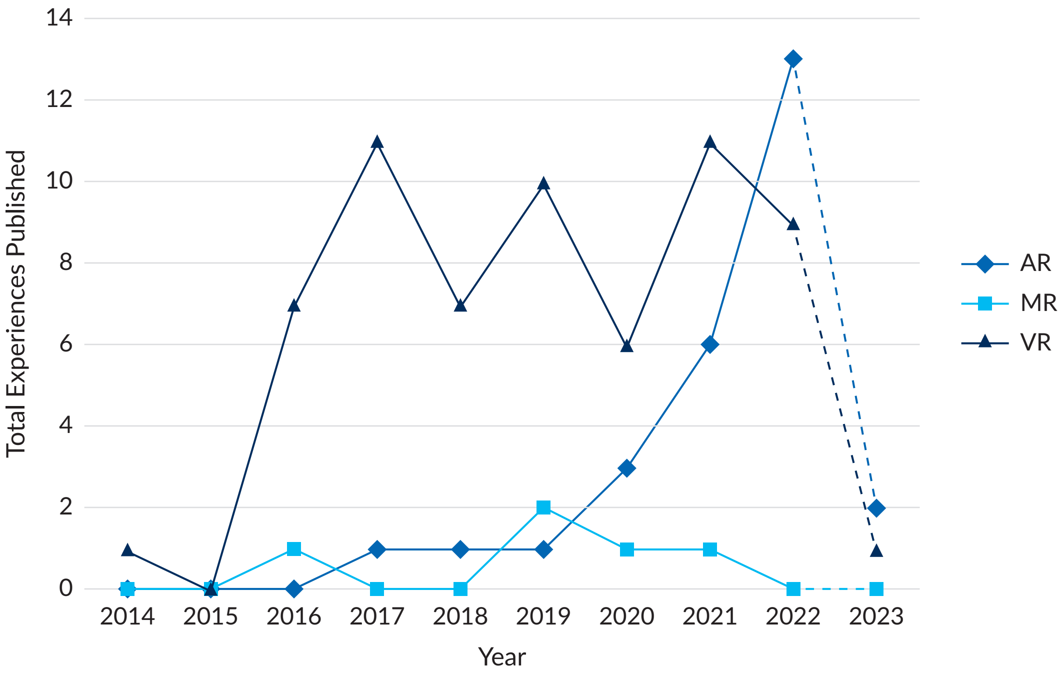

Figure 6. Number of ocean XR experiences, by XR modality, published by year, and accessible at the time of data collection. Notes: The dataset does not present the complete amount of ocean XR content published for 2023, thus, the apparent drop (dotted line) between 2022 and 2023; the dataset only includes ocean XR content available at the time of this study.

The cost of the ocean XR experiences varied greatly. All AR experiences were free. Four MR experiences were free while one cost $50. Roughly a fourth (26.9%) of the VR experiences were for purchase (M = $7.89, SD = 0.99).

Companies are the primary type of entity responsible. They created about two-thirds of the ocean XR content (Figure 7). Fifteen experiences are from individual creators, and 13 are from multiple partners. NGOs are responsible for four ocean XR experiences, and government entities created two.

The ocean XR content came from 26 countries, with 43.6% from the US exclusively, 6.3% from the UK exclusively, 5.3% from Australia exclusively, and the remaining 44.8% from 21 other mainly high-income countries. Only five ocean XR experiences were created at least in part by middle-income countries (World Bank, n.d.). None of the 94 ocean XR experiences were produced by low-income countries. Almost 79% of the ocean XR content is exclusively available in English. French is the second most common language (12.7%), followed by German (10.6%) and Spanish (9.5%). About a quarter (22.3%) of all experiences have more than one language. Most of the AR content is available on smartphones and tablets (iOS or Android),

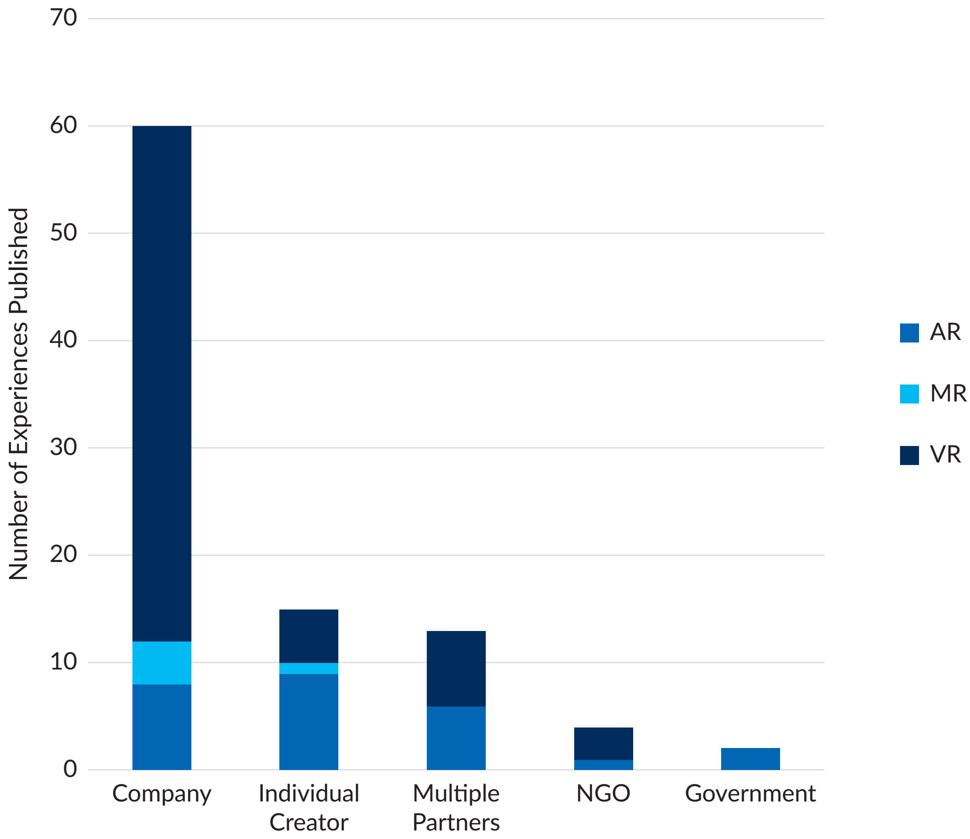

Figure 7. Entities responsible for the development of the ocean XR content by XR modality.

four MR experiences were produced for the Magic Leap 1 HMD, one MR experience was developed for Microsoft's HoloLens, and the ocean VR content is compatible with most HTC and Meta HMDs.

4.2. Ocean XR Features

Analysis of XR experiences yielded insight into the presence of key features according to modality (Table 1).

Table 1. Number (and percentage) of XR experiences with specific features according to modality.

Design features	AR experiences	MR experiences	VR experiences	Total
Multiplayer	0	0	8 (12.70%)	8 (9%)
6 DoF	17 (65.40%)	5 (100%)	59 (93.70%)	81 (8.006%)
Wildlife presence	20 (76.90%)	2 (40%)	52 (82.50%)	74 (79%)
Wildlife interactions	6 (23.10%)	1 (20%)	33 (52.38%)	40 (42.55%)
Environmental interactions	12 (46.20%)	4 (80%)	52 (82.50%)	68 (72%)
Body representation	10 (38.50%)	0	36 (57.10%)	46 (49%)
STEM role	1 (3.80%)	0	27 (42.90%)	28 (30%)
Environmental threat	17 (65.40%)	3 (60%)	25 (39.70%)	45 (48%)

Wildlife depicted in the ocean XR experiences represents a wide range of marine species. Marine invertebrates and fishes are represented equally, with both present in 57% of all experiences. Marine mammals are present in

27 experiences, with whales being the most common, representing 22 of the 40 marine mammals that appear across all content. Of the 93 appearances of fish across all experiences, 24 are sharks. Reptiles, mainly sea turtles, appear in 20 experiences. Plants and protists, including seagrass, mangroves, and algae, were featured in 10 experiences. Birds, including penguins and seagulls, are featured in four experiences. Corals are the most frequently featured invertebrate, present in 30 experiences. Of all 89 appearances of invertebrates, 48 are cnidarians (e.g., corals and jellyfish), 18 are mollusks (e.g., octopuses and squids), and 17 are echinoderms (e.g., sea stars and urchins). Five of the eight marine invertebrate phyla were represented, while the three worm phyla—platyhelminthes, nematodes, and annelids—were not represented. Six XR experiences presented mythical or prehistoric animals (categorized as "other").

4.3. OLPs in Ocean XR Content

Of the 94 experiences, 84 address at least one OLP through narration or gameplay (see Supplementary File, Table B, for percentages of XR experiences addressing between zero and seven OLPs). Table 2 shows how frequently each OLP is addressed in each XR modality. Most AR experiences (80.80%) touch upon OLP6. All the OLPs are included among the 63 VR experiences. The least frequently addressed in VR is OLP2, with only one experience covering it. The most common in VR is OLP5, which is addressed in 66.60% of the VR content. When looking across all XR experiences, OLP6 is most frequently addressed, while OLP4 is the least (see Supplementary File, Table B, for percentages of XR experiences addressing a specific number of OLPs).

Table 2. Number (and percentage) of XR experiences per modality, addressing each OLP.

OLPs	AR experiences	MR experiences	VR experiences	Total
1: Earth has one big ocean with many features	0	3 (60%)	18 (28.60%)	22 (23.40%)
2: The ocean and life in the ocean shape the features of Earth	0	2 (40%)	1 (11.10%)	9 (9.60%)
3: The ocean is a major influence on weather and climate	3 (11.50%)	3 (60%)	8 (12.70%)	14 (14.90%)
4: The ocean makes Earth habitable	2 (7.70%)	3 (60%)	2 (3.20%)	7 (7.40%)
5: The ocean supports a great diversity of life and ecosystems	14 (53.80%)	2 (40%)	42 (66.60%)	58 (61.70%)
6: The ocean and humans are inextricably interconnected	21 (80.80%)	3 (60%)	37 (58.70%)	61 (64.90%)
7: The ocean is largely unexplored	0	0	27 (42.90%)	28 (28.70%)

4.4. OLPs and XR Features

An exploratory correlation analysis was conducted between the OLPs addressed in each ocean XR experience and XR features. Table 3 presents the correlation between variables with Phi coefficients, given the binary nature of the variables. Several design features are positively associated with specific OLPs. For example, 6 DoF is positively associated with OLP1, wildlife presence and interactions are strongly related to OLP5, body representation and assuming a STEM role are strongly related to OLP7, and the presence of environmental threats is positively related to OLPs 3, 4, and 6.

Table 3. Pearson's *R* correlation coefficient matrix between OLPs and design features.

OLP	Multiplayer	6 DoF	Wildlife presence	Wildlife interaction	Environmental interaction	Embodiment	STEM role	Environmental threat
1	−0.17	0.22*	0.10	0.18	0	0.01	0.19	0.17
2	−0.10	0.13	−0.10	0.09	0.04	−0.03	0.03	0.12
3	−0.02	0.08	−0.15	−0.06	0.06	0.07	0.05	0.20
4	−0.09	0.11	−0.15	−0.16	−0.10	−0.12	−0.10	0.22*
5	0.16	0.13	0.66**	0.41**	0.15	0.11	0.18	0.19
6	−0.02	−0.04	0.16	0.05	0.19	0.10	−0.06	0.62**
7	0.06	0.12	0.27**	0.21*	0.18	0.32**	0.66**	0.10

Notes: * Correlation is significant at the 0.05 level (2-tailed); ** correlation is significant at the 0.01 level (2-tailed).

5. Discussion

This study provides the first overview of the characteristics of ocean XR experiences, their affordances for marine education, and their relationship to essential principles of ocean literacy (OLPs).

5.1. The Landscape of Ocean XR

The results show that ocean XR content is characterized by an emphasis on VR, although ocean AR content has seen steady growth since 2018. This could be explained by a general XR industry trend to bolster AR accessibility and content creation, as game engines used to develop mobile AR are enabling easier creation and distribution (Cappannari & Vitillo, 2022). Additionally, advances in 5G communication networks and continued ubiquity of AR-capable smartphones make AR content increasingly accessible, further incentivizing development (Qiao et al., 2019). Contrasting with VR and AR's dominance, ocean MR has stayed anecdotal. MR hardware manufacturers, such as Magic Leap, have shifted away from consumer-facing content, emphasizing enterprise clients (Robertson, 2020).

For-profit companies were the largest source of ocean XR experiences, followed by individual creators. There was a clear relationship between responsible entities and modality: company-created content was largely made for VR, whereas content from individual creators was primarily made for AR. This finding supports the notion that AR is a more accessible modality both for consumers and creators, while also emphasizing the fact that VR development costs are likely manageable by organizations creating ocean XR content for entertainment and revenue. Most consumer-facing VR content has been designed for entertainment, with the most popular genres of VR being action and adventure (Foxman et al., 2021). While the marketplace continues to evolve rapidly, this observation reflects the state of the field as of 2021. While costs varied among ocean XR (with all AR being free), only one of the 94 experiences listed (a VR experience) had in-app purchases. This is consistent with the broader field: in-app purchases are only available in 1% of all commercially available VR experiences (Foxman et al., 2021).

Only 9% percent of all ocean XR experiences analyzed offer multiplayer functionality (one AR and seven VR). Consumers are generally apprehensive about investing in expensive VR headsets for social or multiplayer experiences due to concerns that insufficient adoption by other users will render the device and its multiplayer potential useless (Sykownik et al., 2023). Similarly, integrating multiplayer functionality into XR games comes with the added expense of servers to host multiple users (Amazon, n.d.).

The majority (86%) of ocean XR experiences provide 6 DoF, enabling users to freely roam in their real space, achieving multiple perspectives of digital 3D assets. The ocean XR dataset does not include 360° videos, therefore limiting representation of 3 DoF content in this study. Though this exclusion criterion biases the results towards 6 DoF content, analyzing thousands of available 360° ocean videos was outside the scope of this study.

English is the dominant language, and most of the ocean XR content originated from the US, the UK, Australia, and other high-income countries. This, and the finding that no ocean XR experiences were created in low-income countries, is in line with knowledge that development costs are barriers to creation. A similar bias was highlighted by Shellock et al. (2024) in their systematic mapping of research in OL. They revealed that most research has been conducted by high-income countries (they use the term "global minority"). Future work could investigate whether ocean XR created in high-income countries features marine ecosystems—or targets users—from low-income countries, particularly island nations where the effects of ocean degradation and climate change are disproportionately felt (Intergovernmental Panel on Climate Change, 2022). The biases in ocean XR content creation reflects the ongoing concerns surrounding "parachuting" or "colonial science" in marine research and conservation whereby scientists and NGOs from high-income countries conduct research or deploy programs abroad that "fail to invest in, fully partner with, or recognize local governance, capacity, expertise, and social structures" (de Vos & Schwartz, 2022, p. 1). Therefore, funders and ocean XR creators who seek to contribute to OL and/or marine conservation would benefit from seeking out and supporting partners and XR creators from marginalized communities or based in regions most impacted by ocean issues. The target audience and location of ocean XR content depend on the expected outcomes. An ocean XR experience that portrays the effects of climate change on ocean ecosystems, for instance, may be better aimed at users, industry leaders, and policy makers in the highest-emitting countries like the US and China. Additionally, only 9 of the 94 XR experiences analyzed involve multiple countries, with 13 ocean XR experiences created by multiple partners, further pointing to an opportunity for transdisciplinary collaboration in ocean XR content creation. The potential cultural and international diversity of individual XR creators based in the countries of highest output should not be discounted, as many XR developers in the US, for instance, have emigrated from other countries. Immigrants make up nearly half (45%) of the workforce in Silicon Valley, for example (National Immigration Forum, 2017).

5.2. The Intersection of Ocean XR and OL

A core benefit of ocean XR is how it enables mediated interactions with virtual representations of marine environments and wildlife. While interaction with features in the digital environment (e.g., driving a submarine) was prominent across experiences (72%), interaction with living organisms (e.g., tapping to learn names and lifecycles) was relatively low (42%). This may be due to the costs and technical expertise needed to program human–wildlife interactions and simulate animal behaviors (Zotos et al., 2022).

The majority of ocean XR experiences featured wildlife. Marine mammals like whales and dolphins and seals and sea lions were featured in just under a third of all content. Such charismatic megafauna is well-represented in popular media and is associated with shifts in public perception towards conservation and eco-tourism

(Walpole & Leader-Williams, 2002). The presence of megafauna in ocean XR content might play a similar role in marine education. More experiences featured invertebrates (61%) than marine mammals (29%). This could be because reef-building corals and other benthic invertebrates like sea stars can be conveyed as background and integrated easily into digital settings as 3D assets, whereas animals that swim need to be animated in the experience. Sharks were the most common type of fish across all XR experiences, which is consistent with the prevalence of sharks in popular media (Panoch & Pearson, 2017).

Interaction with real and digital nature has the potential to promote pro-environmental attitudes and behaviors (Hinds & Sparks, 2008); however, our findings show that ocean XR content seldom leverages this affordance. Raja (2023) warns against reducing nature to a backdrop or stage solely for entertainment purposes, a risk illustrated by the limited number of ocean XR experiences that allow interaction with the digital ocean and its inhabitants (note that, in real life, some interactions with marine life, such as grabbing or petting, can be harmful to wildlife, dangerous to humans, and counterproductive to ocean education).

The results show significant correlations between OLPs addressed in ocean XR content and the features of the ocean XR experience itself. OLP7 ("the ocean is largely unexplored") significantly correlates with two features in the ocean XR experiences: embodiment and STEM role. Since OLP7 is focused on exploration, this correlation is driven by the user's ability to step into the role of STEM and technical professionals, for instance, a marine scientist piloting a submersible. While embodiment is associated with OLP7, other principles also benefit from user embodiment. Previous work has shown that embodying a virtual scientist in VR can improve youth engagement with science (Pimentel & Kalyanaraman, 2022). Agency and self-efficacy seem positively correlated when learning in VR (Makransky & Petersen, 2021). Self-efficacy seems to be a driver behind climate change adaptive behavior (van Valkengoed & Steg, 2019), and studies show that embodying a scuba diver can increase ocean acidification knowledge (Markowitz et al., 2018). However, it is worth noting that despite the ubiquity of avatar features in gaming and education, less than half of the ocean XR experiences enabled users to embody a virtual character. Even fewer (30%) placed users in specific STEM or technical roles. This disparity is important considering character embodiment influences information processing in XR (Sakuma et al., 2023), and users' perceptions of their roles in virtual contexts can influence their behaviors (Slater et al., 2010).

OLP7 also correlates with the presence of wildlife and their interactivity. Exploring the ocean, the topic of OLP7, includes encountering and interacting with underwater life. OLP6 ("the ocean and humans are inextricably interconnected") is significantly correlated to the depiction of human-based environmental threats in the ocean XR experiences. As most human impact on the ocean is deleterious, the topic of environmental threats is related to the human–ocean connection. OLP5 ("the ocean supports a great diversity of life and ecosystems") is correlated with the presence of and interaction with wildlife. The presence of different types of wildlife in an experience inherently addresses biodiversity and creates an opportunity for interactivity. Some significant correlations were found for OLP1 ("Earth has one big ocean with many features") and DoF. OLP4 ("the ocean makes Earth habitable") correlates to the presence of an environmental threat. The mechanisms behind these correlations are unknown and further exploration into the intersection of OLPs and XR design features is needed.

Human societies have a growing need to restore ocean health through sustainable behaviors and policies. All available communication and educational tools should be investigated to maximize their contribution to this endeavor. The specific affordances of XR could play a significant role in increasing OL. While the number of available ocean XR experiences and the research about their impact is currently limited, interest from the XR community is growing. We call for this community to further investigate XR for OL. A new theoretical framework could identify how specific XR features facilitate the process of learning specific OLPs. Research shows that embodiment heightens the sense of being there (spatial presence) and being with (social presence; Wirth et al., 2007). The feeling of embodiment is influenced by character roles and by having a salient threat affecting the user in the digital environment (Fribourg et al., 2021). Because embodiment facilitates the user seeing causal relationships between themselves and the virtual context, it could be proposed as contributing to learning about OLP 6 ("the ocean and humans are inextricably interconnected"), which emphasizes codependency between the user and the environment (i.e., the user's survival in the simulated environment can be linked to how the ocean and humans are inextricably interconnected).

Ocean XR creators who seek to enhance OL should avoid superficially relating to OLPs and instead use them to their full potential, for instance by providing details about marine biodiversity when incorporating OLP5, e.g., using interactive imagery, narration, or text that describes and illustrates a green sea turtle's geographical range, its endangered status, or reproductive patterns rather than only featuring a visual representation of a sea turtle. While the public's knowledge about the ocean is important, it is currently insufficient—as evidenced by low OL rates worldwide (Guest et al., 2015). Solely providing information is not enough to trigger behavioral or attitudinal change (Kollmuss & Agyeman, 2002). Ocean XR experiences should therefore go beyond providing facts to offering vicarious nature experience (Kellert, 2002) to enhance connection to marine environments. Such "nature connectedness," defined as the emotional closeness to nature and the feeling of being an integral part of it (Hinds & Sparks, 2008), is crucial to science and environmental learning, and restoring ocean health. Firsthand experience of an environmental issue is more impactful than secondhand information (Spence et al., 2011), as it influences how individuals learn about and perceive risks. Researchers have found a positive correlation between experiencing environmental issues and increased environmental risk perception, pro-environmental attitudes, and behavior (Lang & Ryder, 2016). XR creators have the opportunity to design new ways to meaningfully experience the natural world, especially places that are hard or impossible to visit in person.

5.3. Limitations of the Study

This study has several limitations. The 94 experiences analyzed are unlikely to represent all ocean XR content ever published, as some experiences are no longer available. Accessibility levels are always changing. For instance, LensList, an online database of AR content that was free when we collected the material, is now behind a paywall. Modalities across the spectrum of virtuality were not evenly represented. Most of the dataset consisted of AR and VR content, as we found and analyzed very few ocean MR experiences, making it difficult to identify patterns and draw conclusions about that modality. The 30-minute time limit for each individual coder's playtime may also have affected the results. Though most of the experiences were completed well within that time, some longer experiences may have specific features or OLPs in later stages that the coders missed. The analysis does not measure the extent to which a specific XR experience addresses the content of OLPs. An XR experience briefly touching upon marine diversity by showing various species will be coded similarly to an experience that provides in-depth educational content about the same marine life. While both experiences would align with OLP5 ("the ocean supports a great diversity of life and ecosystems"), the latter has a greater potential to enhance the user's understanding that marine biodiversity is significantly greater than terrestrial biodiversity. We also did not investigate where and how these XR experiences are integrated into formal or informal curricula, if at all. We expect that the effectiveness of ocean XR is enhanced when scaffolded by established teaching methodologies, and we encourage further research into this topic. An additional limitation in this study is that, due to resource limitations, we did not code for the 45 fundamental concepts within the OLPs. Future studies that address these detailed concepts may reveal more nuances in how OLPs are applied in ocean XR. Finally, we coded for embodiment specific to STEM professionals because a large body of research has investigated the impact of embodiment where users specifically take on the role of a STEM professional for learning. We acknowledge that this creates a bias that ignores other identities and expertise relevant in marine education and conservation, for instance, traditional Indigenous knowledge of sustenance fishing. In future work, we encourage researchers to investigate a broader range of cultural representations that are meaningful for OL.

6. Conclusion

This study constitutes the first attempt to visualize the landscape of ocean XR content and assess its potential for improving marine environmental education and promoting OL. Based on this work, we offer three recommendations for future ocean XR content. First, we suggest applying key affordances of XR to offer more meaningful virtual ocean experiences. Second, we encourage more collaborative ocean XR content across disciplines and countries, including equitable partnerships with creators from underrepresented communities. Finally, we suggest conducting further research to examine the causal relationship between key features and learning outcomes, to have a clearer picture of the extent to which ocean XR content can support OL.

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Conflict of Interests
The authors declare no conflict of interests.

Data Availability
The list of the ocean XR experiences, along with the coding, can be found in the OSF project at https://osf.io/8u2xq

Supplementary Material
Supplementary material for this article is available online in the format provided by the author (unedited).

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